# Methodology for a global bicycle real world accidents reconstruction

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**Abstract** - The use of the bicycle on a large scale encouraged in the context to develop an eco friendly environment is facing today on a range of barriers. One of these barriers identified by researchers and governments is observed to include 'road safety'. Hence, it is necessary to set up a protection system for bicyclists especially for the cephalic segment. Currently only few studies are available concerning the head impact loading in case of real accidents. Therefore, the objective of this work is to identify the initial condition of head impact in case of real accident. Head impact velocity and head impact area are extracted and implemented in the last generation of head injury prediction tool to simulate the head trauma by impacting directly the Strasbourg University Finite Element Head Model (SUFEHM) on the vehicle structures. The present study can be divided into three activities i.e. obtain real bicyclist accidents data issued from in depth accident investigation databases, cyclist body kinematic reconstruction to obtain the initial conditions of the head just before the impact and head impact simulation to evaluate the head loading during impact and the injury risk. A total of 26 bicyclists' accident cases with head injuries have been collected from both a French and a German accident database. For each accident case, body kinematic has been simulated using Madymo® software. Two methodologies and human multibody models were used: 10 accident cases have been reconstructed by IFSTTAR using its owned developed human model and 16 accident cases have been reconstructed by Unistra using the human pedestrian TNO model. The results show that the head is impacted more often on top parietal zone, and the mean impact velocity is 6.8 ± 2.7 m/s with 5.5 ± 3.0 m/s and 3.4 ± 2.1 m/s for normal and tangential components respectively. Among these real accidents, 19 cases have been selected to be simulated by finite element computations by coupling the human head model and a windscreen model whose properties were extracted from literature. All reconstructed head impact gave results in accordance with the damage actually incurred to the victims. The objective of this study is to demonstrate the feasibility of numerical reconstruction as an understanding tool of the head impact conditions in bicyclist's accident cases, and hence providing knowledge for helmet optimization using biomechanical criteria.

**Keyword**: In depth accident investigation, Accident reconstruction, bicyclist, Head trauma, Injury risk

## INTRODUCTION

The cyclist accident rate remains high among the whole road users. According to Linn *et al.*'s study in 1998[1], the three parts most often hit during cyclist accident are the arms, legs and head with 50% of cases. Moreover, Otte *et al.*[2]showed that 70% of fatal cases are due to head injuries.

Hence, it is necessary to set up a protection system for bicyclists especially for the cephalic segment. Currently only few information are available concerning the head impact condition for this kind of accidents especially concerning windscreen impact. In 2000 and 2003, Maki *et al.*[3], [4] studied the pedestrian and cyclist kinematics according to the vehicle geometry. It appeared that the impact zones but also the impact velocity and angle were different between cyclist accidents and pedestrian accidents, the authors concluded that the existing pedestrian tests were not applicable to cyclists. In 2001, Werner *et al.*[5]studied the human-cycle decoupling human-cycle. He showed that in case of off-center impact or a cycle velocity over 5 m/s, the cyclist was often thrown to the ground without touching the car. Moreover, its kinematics is largely influenced by the position of the leg at the time of impact. Overall it appeared that the head impact velocity was 0.8 times the vehicle velocity when the head impacted the car. Several authors have reconstructed many accidents between car and bicyclists in order to identify the bicyclist kinematics during impact, as Serre *et al.* in 2007 [6]. However, bicyclist falls that occur on their own have not been studied because of the wide range of possible scenarios and the difficulty of categorizing them. Therefore, the objective of the present work is to identify the initial condition of head impact for a number of real world accident cases against vehicles.

## MATERIALS AND METHODS

The present study can be divided into three activities i.e. obtain real bicyclist accidents data issued from in depth accident investigation databases, cyclist body kinematic reconstruction to obtain the initial conditions of the head just before the impact and head impact simulation to evaluate the head loading during impact and the injury risk. A total of 26 bicyclists' accident cases with head injuries have been collected from both a French and a German accident database. For each accident case, body kinematic has been simulated using Madymo® software. Two methodologies and human multibody models were used: 9 accident cases have been reconstructed by IFSTTAR using its owned developed human model and 18 accident cases have been reconstructed by Unistra using the human pedestrian TNO model. Among these cases, one same accident have been reconstructed by the both institutes in order to compare the methodologies. The main objective of the multibody simulation is to compute the victim's kinematics from which the initial head velocity and position are implemented on a human head finite element model in order to simulate the impact on the structure (bonnet, windscreen, road, *etc.*) and this constitutes the third step. All finite elements simulations are performed under RADIOSS® software using the Strasbourg University Finite Elements Head Model (SUFEHM) in order to calculate the mechanical parameters associated to the head injuries criteria. The aim of this last step is to compare the injury parameters with the lesions actually observed on the motorcyclist.

The IFSTTAR research unit of Accident Mechanism analysis investigates road accidents since 1980 [7–9]. The IFSTTAR in depth accident investigation database EDA (Études Détaillées d'Accidents) contains about 1000 accidents including 28 cases involving cyclists. Among these bicyclist's accidents, five died with head injuries and only seven wore a helmet. Although these accidents are not a representative pattern of all bicyclist's accidents, they constitute an illustration of the diversity of accidents. Because of the complexity of several cases, 13 accident cases have been selected to be reconstructed with a multi body software, as reported in table 1.

| | Accident cases | Impact on Vehicle | Impact on Bicyclist. | Vehicle velocity [km/h] | Bicycle velocity [km/h] | Head AIS | Helmeted |
|---|---|---|---|---|---|---|---|
| 1 | IFSTTAR 1994038 | Frontal | Frontal | 40-50 | 10-20 | 1 | No |
| 2 | IFSTTAR 1995012 | Frontal | Frontal | 50-70 | 10-20 | 2 | No |
| 3 | IFSTTAR 1995042 | Frontal | Lateral | 40-50 | 5-15 | 5 | No |
| 4 | IFSTTAR 1996011 | Frontal | Frontal | 10-20 | 15-25 | 1 | No |
| 5 | IFSTTAR 1998008 | Lateral | Frontal | 10-15 | 15-25 | 0 | No |
| 9 | IFSTTAR 1999009 | Frontal | Lateral | 15-25 | 15-25 | 2 | No |
| 7 | IFSTTAR 1999108 | Frontal | Lateral | 50-70 | 0-10 | 3 | Yes |
| 8 | IFSTTAR 1999111 | Frontal | Lateral | 60-80 | 5-15 | 5 | No |
| 9 | IFSTTAR 2004025 | Frontal | Lateral | 50-70 | 5-15 | 1 | No |
| 10 | IFSTTAR 2005027 | - | fall alone | - | 20-30 | 1 | No |
| 11 | IFSTTAR 2005048 | Frontal | Lateral | 5-10 | 15-25 | 2 | Yes |
| 12 | IFSTTAR 2007024 | Frontal | Lateral | 10-15 | 15-25 | 1 | No |
| 13 | IFSTTAR 2011005 | - | fall alone | - | 0 | 1 | No |

Table 1. Summary report of bicyclist's accidents selected from IFSTTAR EDA database.

GIDAS (German In-Depth Accident Study) is the largest database of accident cases in Germany. Accidents collected from the Medical University of Hanover are reported in table 2. All cases come from the outskirts of Hanover, Germany. A total of 13 cases were selected. Thus, a total of 26 were selected for reconstruction. Among the 26 analyzed cases, the bicyclist had an AIS 1 on 17 cases, AIS 2 on 4 cases, AIS 3 on 2 cases, AIS 5 on 2 cases and one case without head injury.

| | Accident cases | Impact on Vehicle | Impact on Bicyclist. | Vehicle velocity [km/h] | Bicycle velocity [km/h] | Head AIS | Helmeted |
|---|---|---|---|---|---|---|---|
| 1 | GIDAS 30000396 | Frontal | Lateral | 20-30 | 5-15 | 1 | No |
| 2 | GIDAS 30001006 | Frontal | Frontal | 20-30 | 10-20 | 1 | No |
| 3 | GIDAS 30010254 | Frontal | Lateral | 20-30 | 15-25 | 1 | No |
| 4 | GIDAS 30010769 | Frontal | Lateral | 10-20 | 5-15 | 1 | No |
| 5 | GIDAS 30020735 | Frontal | Lateral | 30-40 | 15-25 | 1 | No |
| 6 | GIDAS 30030355 | Lateral | Frontal | 30-40 | 15-25 | 1 | No |
| 7 | GIDAS 30040160 | Frontal | Lateral | 30-40 | 10-20 | 1 | No |
| 8 | GIDAS 30040550 | Frontal | Lateral | 30-40 | 5-15 | 2 | No |
| 9 | GIDAS 30040580 | Frontal | Lateral | 50-70 | 5-15 | 3 | No |
| 10 | GIDAS 30040584 | Frontal | Frontal | 30-40 | 15-25 | 1 | No |
| 11 | GIDAS 30050161 | Frontal | Lateral | 10-30 | 0-15 | 1 | No |
| 12 | GIDAS 30060174 | Frontal | Lateral | 10-30 | 10-20 | 1 | No |
| 13 | GIDAS 30060641 | Frontal | Lateral | 25-45 | 0-10 | 1 | No |

Table 2. Summary report of bicyclist's accidents selected from GIDAS database.

The second step of this work is to reconstruct the accidents under two methodologies (IFSTTAR and Unistra methodologies). These reconstructions are carried out with Madymo® software in both cases. The principle of solving multi-body system is to define a set of rigid bodies represented by ellipsoids and connected by joints. Unlike finite elements, contact between two bodies is not computed by deformable surfaces but by a penetration force defined by a function. The computational time of this multi-body approach is strongly reduced in comparison with FE simulation. The models are developed using ellipsoids in such a way that the geometry, mass and inertia are respected.

## *IFSTTAR* modeling

The accident modeling uses three independent multi body systems: the bicyclist, the bicycle and the antagonist vehicle. The bicyclist was developed by IFSTTAR and is composed of 35 rigid bodies, 35 joints and 82 surfaces. The mechanical characteristics of each joint are based on the biomechanical database of literature (Serre *et al.*[10]).The human model was scaled to the victim for each accident case. The bicycle model consists of two rigid bodies articulated by a joint in order to represent the rotation of the front wheel as well as the handlebar. It consists of 31 ellipsoid surfaces, as illustrated in figure 2a.Concerning the vehicle, it consists of front face including bumper bonnet and windscreen of a typical European tourist car. Its geometry is defined by 14 parameters obtained from constructor’s database and direct measures on vehicles, as illustrated in figure 1.The mechanical characteristics of the surfaces are obtained from experimental tests as well as literature.

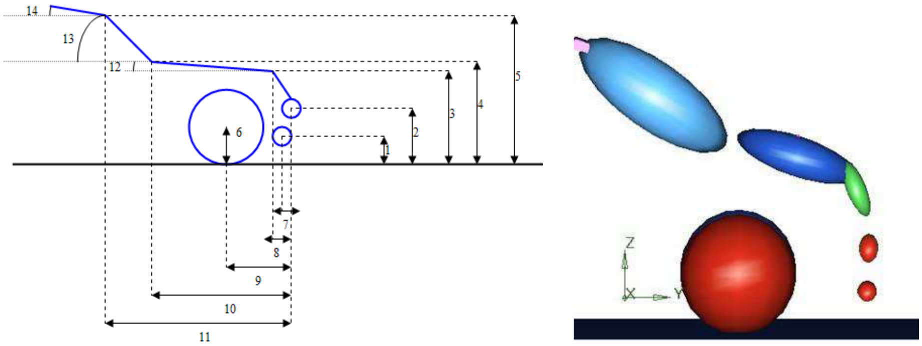
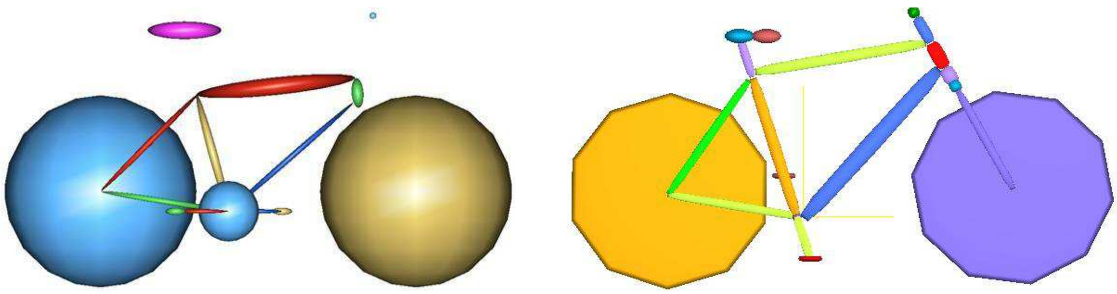



Figure 1.Representation of the IFSTTAR vehicle modeling.

## *Unistra modeling*

The human model used was the scalable TNO Pedestrian model implemented in Madymo® package and validated against post mortem human tests, as depicted by Hoof *et al.* in 2003 [11] and De Lange *et al.* in 2005 [12].It consists of 64 ellipsoids and 52 rigid bodies linked together by 20 joints. The vehicles models are developed using ellipsoids in such a way that the geometry is respected. The contact force functions used on each part of the car are extracted from the study of Martinez *et al.*,2007 [13], as illustrated in figure 3. The bicycles are modeled in accordance with geometry, mass. Each part of the frame was modelled by a rigid body including mass and inertia computed as steel pipes and connected by “bracket” joints. The frame and the front fork as well as the frame and the pedalboard were connected by a revolute joint (figure 2b).



(a) (b)

Figure 2. Representation of the bicycle models (a) for IFSTTAR and (b) for Unistra.

Figure 3.Car modeling with superimposition of ellipsoids on car geometry, and representation of force-deflection curves for (a) bumper, (b and c) bonnet and windscreen (d).

### *Methodoly*

The basis of the reconstruction method is the same for both teams. That differs is the means used as models or parametric analysis. Hence, the main step of the reconstruction methodology is described as following and depicted in figure 4:

- defining the parameters and fields of study,
- modeling the accident,
- analyzing the parametric study,
- determining the most likely configuration by comparing WAD (Wrap Around Distance), bicyclist throw distance as well as impact are on both vehicle and victim from simulation to real case. These check points allow validating the considered accident reconstruction.
- Extracting the head initial output just before contact.

Figure 4.Methodology applied to extract the initial head impact condition from a real accident case.

The considered outputs are the head initial position and speed before impact as well as the impact location on the antagonist. These output data were introduced in the Strasbourg University FE Head

Model (SUFEHM) in order to simulate the head trauma as illustrated in figure 5

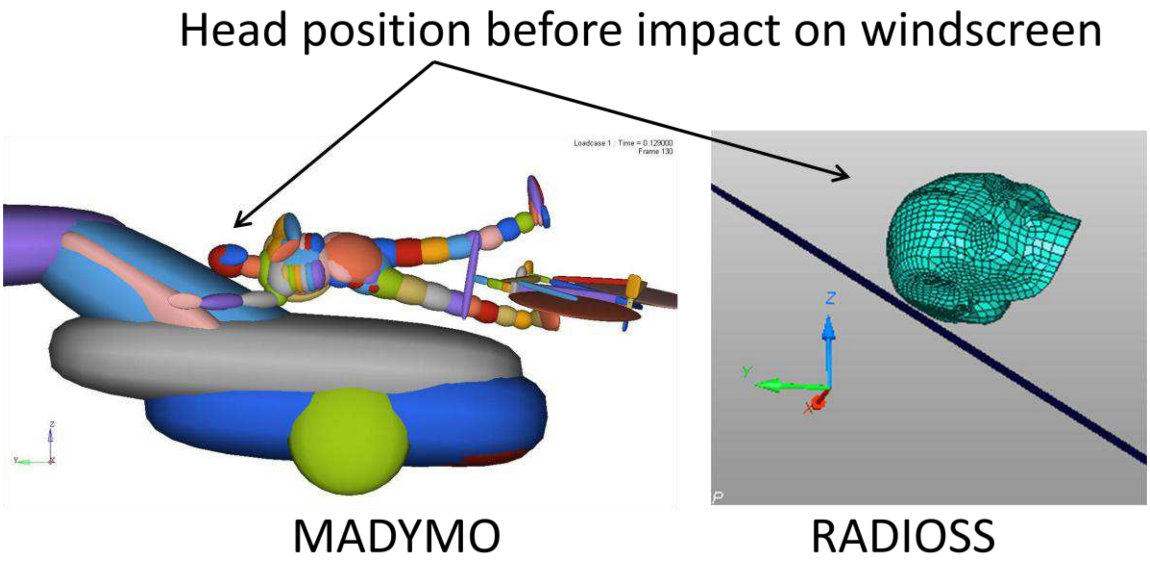



figure 5. It includes the main anatomical features: skull, falx, tentorium, subarachnoid space, scalp, cerebrum, cerebellum, brain stem. Falx and tentorium have a layer of shell elements, skull is simulated by three layered composite shell and the others were constituted by brick elements. The finite element mesh is continuous and represents an adult human head. The subarachnoid space was modeled between the brain and the skull to simulate the cerebral-spinal fluid. This space is constituted by a layer of brick elements and surrounds entirely the brain. The tentorium separates the cerebrum and cerebellum and the falx separates two hemispheres. A layer of brick element simulating the cerebral-spinal fluid surrounds theses membranes. The scalp was modeled by a layer of brick elements and surrounds the skull and facial bone. Globally, the present human head model consists of 13208 elements. Its total mass is 4.5 kg. Material properties assigned to the different parts are all isotropic, homogenous and elastic. The tolerances limits have been established by reconstructing 68 cases of real accidents. The obtained limits as well as the mechanical parameters associated are presented in work of Deck *et al.* (2008) [14].

Coming to the head injury assessment SUFEHM and related injury criteria [15] have been used. The computation of head injury based on Von Mises stress, intracranial pressure and internal energy have been compared with the injuries sustained by the victim in order to validate the global accident reconstruction process.

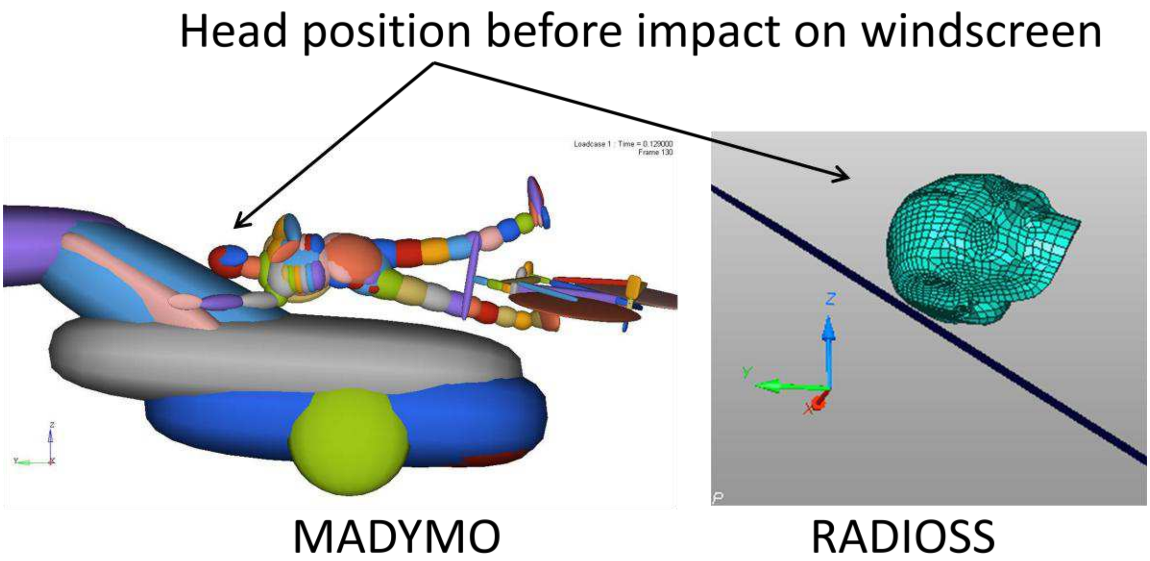


Figure 5. Initial configuration of the head impact in accordance with Madymo® simulation and FE simulation of the head trauma.

## RESULTS

A total of 26 accident cases have been reconstructed with multibody simulations and the results in terms of relative head impact velocity and impact zone are reported in for the IFSTTAR simulations and for the Unistra ones. These tables relate the relative head impact and the head impact angle calculated with respect to the normal to the contact surface as well as the head impact area. Figure 6 shows the distribution of head impacts area for all 26 reconstructed cases. It is observed that in more than 35% of cases, the impact is in superior parietal area. The average speed for antagonist was about 8.9 ± 3.5 m/s and for the bicyclist it was about 3.3 ± 1.6 m/s. The average velocity of the head just before contact is 6.7 ± 2.7 m/s which can be decomposed into 5.5 ± 2.9 m/s and 3.5 ± 2.0 m/s for respectively normal and tangential components. The head impact angles are distributed as shown in figure 7 and centered at 33 ± 20 deg.

The results of one real accident case reconstructed by both research units are compared in table 5. There are few differences about resultant and normal head impact velocity. The main difference appears at tangential velocity.

| | Accident cases | $V_{resultant}$ [m/s] | $V_{normal}$ [m/s] | $V_{tangential}$ [m/s] | Head Impact Angle [deg] | Head Impact Area | |
|---|---|---|---|---|---|---|---|
| | | | | | | Latitude | Longitude |
| 2 | IFSTTAR 1996011 | 6.9 | 3.3 | 6.1 | 62 | 1 | 2 |
| 3 | IFSTTAR 2004025 | 6.3 | 6.2 | 1 | 9 | 2 | 2 |
| 4 | IFSTTAR 2005048 | 4.8 | 3.5 | 3.2 | 42 | 1 | 3 |
| 5 | IFSTTAR 2007024 | 6.7 | 5.9 | 3.1 | 28 | 4 | 2 |
| 6 | GIDAS 30000396 | 3.6 | 3.5 | 0.5 | 8 | 1 | 2 |
| 7 | GIDAS 30001006 | 7.7 | 6.6 | 4 | 31 | 3 | 2 |
| 8 | GIDAS 30010254 | 8.7 | 5.2 | 7 | 53 | 2 | 1 |
| 9 | GIDAS 30010769 | 2 | 1.5 | 1.3 | 41 | 2 | 2 |
| 10 | GIDAS 30020735 | 5.6 | 5.4 | 1.5 | 16 | 1 | 2 |
| 11 | GIDAS 30030355 | 5 | 4.5 | 2 | 24 | 4 | 3 |
| 12 | GIDAS 30040160 | 10.6 | 10.5 | 0.9 | 5 | 2 | 2 |
| 13 | GIDAS 30040550 | 9.3 | 9.2 | 1.5 | 9 | 3 | 2 |
| 14 | GIDAS 30040580 | 13.8 | 11.8 | 7.1 | 31 | 3 | 3 |
| 15 | GIDAS 30040584 | 10.7 | 10.3 | 2.9 | 16 | 3 | 1 |
| 16 | GIDAS 30050161 | 4 | 3.9 | 1 | 14 | 1 | 2 |
| 17 | GIDAS 30060174 | 4 | 2.7 | 3 | 48 | 3 | 1 |
| 18 | GIDAS 30060641 | 8.9 | 7.3 | 5.2 | 35 | 4 | 3 |
| | Mean Values | 7.2 ± 3.0 | 6.1 ± 3.0 | 3.2 ± 2.1 | 28 ± 16 | 2.5 ± 1.1 | 2.1 ± 0.7 |

Table 3. Results of the head impact from the Unistra multibody reconstructions.

| | Accident cases | $V_{resultant}$ [m/s] | $V_{normal}$ [m/s] | $V_{tangential}$ [m/s] | Head Impact Angle [deg] | Head Impact Area | |
|---|---|---|---|---|---|---|---|
| | | | | | | Latitude | Longitude |
| 2 | IFSTTAR 1995012 | 4.5 | 2.8 | 3.5 | 50 | 1 | 2 |
| 3 | IFSTTAR 1995042 | 5.4 | 4.5 | 3.1 | 34 | 2 | 2 |
| 4 | IFSTTAR 1998008 | 5.2 | 5.7 | 6.2 | 22 | 1 | 2 |
| 5 | IFSTTAR 1999009 | 7.1 | 3.7 | 6.1 | 59 | 2 | 3 |
| 6 | IFSTTAR 1999108 | 7.3 | 4.1 | 6.0 | 56 | 2 | 3 |
| 7 | IFSTTAR 1999111 | 8.8 | 7.8 | 3.9 | 26 | 1 | 2 |
| 8 | IFSTTAR 2005027 | 2.5 | 0.3 | 2.9 | 84 | 3 | 3 |
| 9 | IFSTTAR 2011005 | 4.4 | 4.1 | 1.7 | 23 | 2 | 2 |
| | Mean Values | 5.8 ± 1.8 | 4.2 ± 2.5 | 4 ± 1.8 | 43 ± 25 | 1.7 ± 0.7 | 2.3 ± 0.5 |

Table 4. Results of the head impact from the IFSTTAR multibody reconstructions.

| Accident cases | $V_{resultant}$ | $V_{normal}$ | $V_{tangential}$ | Head Impact | Head Impact Area |
|---|---|---|---|---|---|

| | | | [m/s] | [m/s] | [m/s] | Angle [deg] | Latitude | Longitude |
|---|---|---|---|---|---|---|---|---|
| IFSTTAR 1994038 | 1 | Unistra | 6.9 | 5.2 | 4.6 | 42 | 3 | 3 |
| | 1 | IFSTTAR | 6.8 | 6.6 | 1.7 | 14 | 2 | 2 |

Table 5. Results of the head impact from the three real accident cases reconstructed by both IFSTTAR and Unistra.

Figure 6. Representation of the head impact area distribution for the 26 accident reconstructions.

Figure 7. Representation of the head impact angle distribution for the 26 accident reconstructions

In 19 accident cases the head impacts windscreen *i.e.* 73% of the 26 accident cases. In this study only windscreen impact were considered to simulate the head impact with a head finite element model. The head model used for these simulations was the Strasbourg University Finite Element Head Model (SUFEHM) developed by Kang *et al.* 1997 [16].

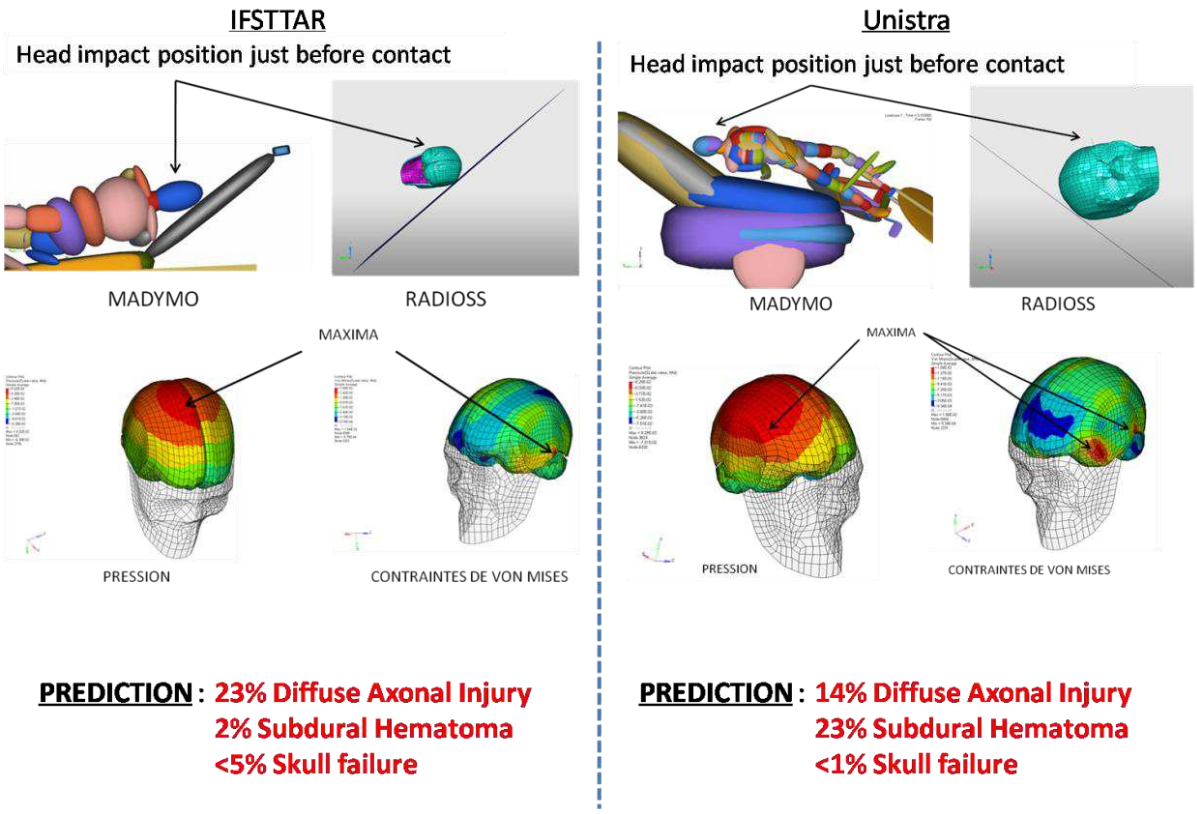



Figure 8. Representation of the methodology to simulate the head trauma applied to both IFSTTAR and Unistra head initial conditions.

For most of the cases without unconsciousness of the victim, the numerical simulation predicted well the head injury as reported in table 6. Similarly, cranial fracture was correctly reproduced when it was present. This later result permits it to validate the whole methodology involving accident analysis-multibody reconstruction – FE simulation.

Concerning the common real accident case, the injury risks observed are in accordance with the real injuries and similar for both research units

| CASES | Head MAIS | Injury Risks % | | |
|---|---|---|---|---|
| | | Moderate Diffuse Axonal Injury | Subdural Hematoma | Skull Failure |
| IFSTTAR 1994038 | 1 | 14 (Unistra)<br>23 (IFSTTAR) | 23 (Unistra)<br>2 (IFSTTAR) | <1 (Unistra)<br><5 (IFSTTAR) |
| IFSTTAR 1995042 | 5 | 100 (IFSTTAR) | 88 (IFSTTAR) | 100 (IFSTTAR) |
| IFSTTAR 2004025 | 1 | <1 (Unistra) | 4 (Unistra) | <1 (Unistra) |
| IFSTTAR 1995012 | 1 | 23 | 2 | <1 |
| IFSTTAR 1999108 | 1 | 31 | 14 | <1 |
| IFSTTAR 1999111 | 2 | 80 | 7 | 12 |
| IFSTTAR 1996011 | 5 | 26 | 11 | <1 |
| GIDAS 3001006 | 1 | 81 | 18 | <1 |
| GIDAS 3060174 | 1 | <1 | 3 | <1 |
| GIDAS 3020735 | 1 | 1 | 5 | <1 |
| GIDAS 3030355 | 1 | <1 | <1 | <1 |
| GIDAS 3050161 | 1 | <1 | 1 | <1 |
| GIDAS 3040580 | 3 | 91 | 16 | 37 |
| GIDAS 3040550 | 2 | 10 | 10 | <1 |
| GIDAS 3000396 | 1 | <1 | 9 | <1 |
| GIDAS 3010254 | 1 | 10 | 5 | 33 |
| GIDAS 3060641 | 1 | 10 | 5 | 43 |
| GIDAS 3040584 | 1 | 10 | 8 | <5 |
| GIDAS 3040160 | 1 | <1 | 21 | <5 |

Table 6. Head trauma simulation results for the 19 reconstructed real accidents, the boxes in red indicate a discordance between the predict injury risk and the real injury.

## SYNTHESIS AND DISCUSSION

Real world accident reconstructions remain a key issue in studying the kinematic of bicyclist during impacts. Indeed, the selection of the most likely scenario determines the initial position and velocity of the head just before impact. The quantitative values related to the cyclist's head impact provide important initial conditions for windscreen and bicycle helmet design.

Main limitation of the present study is the fact that for the majority of the accident cases the victim presented an AIS 1. It is therefore obvious that a higher number of accident cases should be considered in a further step. The present analysis gives new insight in the cyclist versus car head trauma and focuses on the first impact. Further investigation considering the second impact (such as the ground fall) is also needed in a further approach.

This work provides a full methodology for numerical reconstruction of cyclist’s real accidents as well as a solid information base for future work to carry on bicyclists’ accidents. An automatic parametric analysis was implemented to study the effects of environmental parameters poorly known in real world situation such as head initial position or velocity and impact location. The results permit to evaluate automatically all possible scenarios during the reconstruction of these accidents and to extract the most likely scenario based on accident data. In particular the tangential component of the velocity vector should be considered in future helmet standard test.

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